

An Interacting O+O Supergiant Close Binary System: Cygnus OB2-5 (V729 Cyg)

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Abstract

The massive interacting close binary system V729 Cyg (OIa+O/WN9), plausibly progenitor of a Wolf-Rayet system, is studied using new observations gathered over 65 nights and earlier published data. Radial velocity and five colour light curves are analysed simultaneously. Estimated physical parameters of the components are $M_1 = 36 \pm 3 M_\odot$, $M_2 = 10 \pm 1 M_\odot$, $R_1 = 27 \pm 1 R_\odot$, $R_2 = 15 \pm 0.6 R_\odot$, $\log(L_1/L_\odot) = 5.59 \pm 0.06$, and $\log(L_2/L_\odot) = 4.65 \pm 0.07$. We give only the formal 1σ scatter, but we believe systematic errors in the luminosities, of uncertain origin as discussed in the text, are likely to be much bigger. The distance of the Cygnus OB2 association is estimated as 967 ± 48 pc by using our newly obtained parameters.

Keywords: Stars: binaries -stars: binaries: close - stars: individual: V729 Cyg - stars: fundamental parameters -stars: early-type - Galaxy: open clusters and associations: individual: Cygnus OB2

1. Introduction

One of the nearest ($d < 1.5$ kpc) OB associations, Cygnus OB2 contains some of the most massive and luminous stars of our Galaxy. Cygnus OB2 most probably belongs to Cygnus-X, one of the richest massive star forming regions. Earlier studies showed that the Cygnus OB2 region contains a number of O, B, and Wolf-Rayet stars. The total mass of the association is about 30,000 M_\odot (Wright et al. 2012). The age of the cluster was estimated to be in the range 1-10 Myr. Massey et al. (1995) gave an age of 1-4 Myr and recently Wright et al. (2010) give its age as 3.5-5.3 Myr. The Cygnus OB2 association is a good laboratory to study star formation and stellar evolution, including the most advanced stages of the evolution of massive

stars. Hence, the association has been observed in γ -ray, X-ray, UV, optical, IR, and radio wavelengths in numerous studies. Nevertheless the interstellar medium affects the observations, especially in the UV and optical part of the electromagnetic spectrum (Rauw 2011).

The distance of the association has been calculated by various methods and these show differences. Kiminki et al. (2007) calculated the visual extinction (A_V) as 5.4 mag and the distance modulus as 11.3 mag, by analyzing 146 OB systems. Linder et al. (2009) have calculated the distance of the cluster as 925(25) pc from a photometric analysis of the Cygnus OB2-5 system. In the literature different results derived by various methods exist (see Rauw 2011). These discrepancies possibly reflect the differences between the methods used as well as the differences in the estimation of the visual extinction. In this study, we obtain a new estimate of the distance, using our new photometric data of the eclipses

V729 Cyg (Cygnus OB2-5=BD+40°4220, $P = 6.6$ days) is a member of the association and a massive and high-temperature contact binary (HTCB), and has been discussed in many studies since it was discovered (e.g. Wilson 1948, Wilson & Abt 1951, Hall 1974, Bohannan & Conti 1976, Leung & Schneider 1978, Vreux 1985, Rauw et al. 1999, Linder et al. 2009). The binary system consists of two supergiant components. Recently, Kennedy et al. (2010) reported indirect evidence for the presence of a third body in V729 Cyg with an orbital period of 6.7 years.

The UBV light variations of the system were obtained by Hall (1974) and later these light variations were used by Leung & Schneider (1978) to model its light curve using the Wilson-Devinney code (Wilson & Devinney 1971, hereafter W-D code). Leung & Schneider (1978) then calculated the orbital and physical parameters of the system by using Bohannan & Conti radial velocities. They gave the masses of the components as $M_1 = 58.7 \pm 9.1 M_\odot$ and $M_2 = 13.7 \pm 6.3 M_\odot$.

Vreux (1985) reported a periodic change in the H_α profile. Rauw et al. (1999) measured the radial velocities of the binary components and studied the emission line profile variations caused by the stellar wind interactions. They derived the mass functions for the components as $M_1 \sin^3 i = 24.6 M_\odot$ and $M_2 \sin^3 i = 6.9 M_\odot$ and the mass loss rate of the stellar winds as $\dot{M}_1 = 5.0 \times 10^{-6} M_\odot/\text{yr}$ and $\dot{M}_2 = 5.5 \times 10^{-6} M_\odot/\text{yr}$. They gave the spectral types of the components as O6.5-7 Ia+Ofpe/WN9. Linder et al. (2009) investigated the light variations of the system at 5057 Å and 6051 Å. Assuming a bright spot Linder et al. modelled its LC with the Nightfall software. The authors

estimated the masses of components as $M_1 = 31.9 \pm 3.2 M_\odot$ and $M_2 = 9.6 \pm 1.1 M_\odot$, values with which we largely agree.

In this study newly obtained 5-colour (UBVRI) light curves of the system, published UBVR light curves of Hall (1974), and radial velocity curves from Rauw et al. (1999) are analysed simultaneously and the orbital, physical parameters and the distance of the association are presented. Following the observational information given in the second section, light and radial velocity models are presented in the third section and in the fourth section physical parameters of the binary system are calculated.

2. New Observations

The light variations of V729 Cyg were observed in the Bessel U, B, V, R and I bands over 65 nights between August 2010 and October 2011. The observations were carried out at the TÜBİTAK National Observatory (TUG) with the 60cm telescope, which was equipped with an FLI CCD with 2048×2048 pixel. Comparison stars selected from the literature were GSC 3161-01269 and GSC 03161-01384. A total of 272, 417, 451, 281, and 280 data points were obtained in U, B, V, R and I bands, respectively.

The IRAF (DIGIPHOT/APPHOT) packages were used in data reduction. The reduction and analysis of each frame are performed by subtracting the standard bias frames, dark frames, and dividing by flat-field frames, followed by aperture photometry. During the reduction, we have studied all the nights and each frame separately. Standard deviations of the data are estimated as $0^m.030$, $0^m.010$, $0^m.010$, $0^m.008$, and $0^m.009$ for the *U*, *B*, *V*, *R* and *I* bands, respectively.

All the new observations are given in Table 1. The entire table can be found at the CDS database. In Fig. 1 we show the *UBVRI* light curves of V729 Cyg. The UBVR light curves of Hall (1974) are also plotted in Fig. 1 (namely as U_H , B_H , and V_H). In Fig. 1 we plotted phase *vs.* relative flux instead of magnitudes. During data reduction, we used the linear ephemeris

$$\text{Min I} = 24\,40413.821(38) + 6.597887(28) \times E, \quad (1)$$

which is a reasonable approximation, over the last 40 years, to the quadratic ephemeris obtained over 115 yrs in the next Section. Subsequently the code gave an improved period of 6.597981, which is still in good enough agreement with our quadratic ephemeris over the 40 yr time span.

3. Eclipse timings and period study

Detection of times of minima of long period eclipsing binary systems like V729 Cyg have relatively low probability. Hence the times of minima of V729 Cyg obtained during the last century are not as numerous as for other kinds of binaries. To search for the possible causes of observed period variations one should study their O-C variations (O, Observed; C, Calculated minima times). This variations can bear information about the origin of the orbital period variation. In this study, we collected all the minima times from the literature and list them in Table 2, along with the one obtained in this study. We have not included the minima times of the system given by Kurochkin (1961) since they are given only to two digits and are highly scattered. The data in Table 2 span over a 115 years, and so covers an important amount of time in the context of high-mass stellar evolution. The O-C variations show an upward parabolic trend. This indicates an increase in orbital period, which can occur when mass transfer takes place from the less massive star to the more massive one in a semidetached configuration; but a period increase can also be expected if one or both components is losing mass to infinity through stellar wind in a detached configuration. In addition if a third body orbits the binary system there can be a long period high amplitude oscillation. However, the possibility of this is quite low since no such variation has been ever detected.

A weighted least-squares method applied to the O-C timings (Fig. 2a) gives a quadratic solution:

$$\begin{aligned} \text{HJD} &= \text{HJD}_o + P_o E + \frac{1}{2} \frac{dP}{dE} E^2 \\ &= 24\,56103.646(38) + 6.598074(12) \times E + 6.3(6) \times 10^{-8} \times E^2 \end{aligned} \quad (2)$$

The residuals are shown in Fig. 2b. This result indicates an orbital period variation on a timescale $P/\dot{P} \sim 9.4 \times 10^5$. We do not detect the third-body period of 6.7 yrs suggested by Kennedy et al (2010).

4. Light curve modeling

We have reduced the observed magnitude to relative flux before light variation analysis. We did a similar process to the Hall (1974) UBV data. Later we determined the weights by taking in to consideration the observational

errors. According to this we determined the weights for U, B, V, R, and I filters respectively as 3.3, 10, 10, 12.5, and 11.1. We used the Phoebe (Prša & Zwitter 2005) program based on the W-D code. In the analysis the radial velocity data from Rauw et al. (1999), as well as the Hall (1974) UBV observations and the UBVR observations obtained in this study were used.

During the analysis the temperature of the primary component, the limb darkening (van Hamme 1993), albedos (Rucinski 1969) and gravity darkening (von Zeipel, 1924) are regarded as fixed parameters. The temperature of the primary component was assumed as either 36000 K from the spectral study of Rauw et al. (1999), or 32000 K. The latter value is appropriate for O9I (Cox 2000). The time of minimum light T_0 , orbital period P , orbital inclination i , mass ratio q , temperature of the secondary component T_2 , surface potentials $\Omega_1 = \Omega_2$, luminosities $L_1(\text{U})$, $L_1(\text{B})$, $L_1(\text{V})$, $L_1(\text{R})$, $L_1(\text{I})$, $L_1(\text{U1})$, $L_1(\text{B1})$, $L_1(\text{V1})$ are free parameters to be solved for. The results are summarized in Table 3. The analysis indicates that the light contribution of the primary component is 86% in U, 85% in B, V and R, and 84% in the I-light curve, for our 32000K solution. In Fig. 1 the light curves computed with the resulting parameters are shown by solid lines. Modeling of the system indicates Roche-lobe overfilling components. The filling factor, $f = 0.22$ or 0.17 , is given by $(\Omega_{\text{in}} - \Omega)/(\Omega_{\text{in}} - \Omega_{\text{out}})$, and varies from zero to unity from the inner to the outer critical surface. This solution indicates that the system has a moderate degree of contact.

5. Astrophysical parameters of the system

The speed of the center of mass, V_γ , averages as -55 . That the two components are best represented by somewhat different V_γ 's probably represents the fact that winds from each component have different speeds, and so distort and shift the lines differently. Although the colors such as B-V vary rather little round the orbit, as can be seen in Fig. 1a, the temperatures are required to differ because of the different geometries of the two eclipses.

The physical parameters of V729 Cyg listed in Table 4 are determined from the parameters of Table 3. The temperature of the Sun was taken as 5777 K and its bolometric magnitude as 4.732 mag.

In order to obtain the absolute visual magnitude the bolometric corrections (BC) are estimated from Martins et al. (2005). The total magnitude of the system is taken as $V=9.21$ mag (Hall 1974), and the individual magnitudes as 9.41 and 11.15. The E_{B-V} value (1.99 ± 0.03) of the system was

obtained from Friedman et al. (2011). Using the apparent magnitude of the system and the values quoted in Table 4, we infer the distance of the system to be 967 ± 48 pc. Distance estimation from the binary parameters gives a result that is consistent with the other distance estimation techniques (see Section 1).

6. Results and Conclusion

In this study we investigated the massive interacting close binary system V729 Cyg by using our new and earlier published observations. Radial velocity and light curves of the system were solved simultaneously, and the orbital and physical parameters obtained are shown in Table 3 and Table 4. Our analysis shows that the system has a moderate contact configuration.

In their studies on X-ray and radio emission, Linder et al. (2009) and Kennedy et al. (2010) suggested that there is a third body with a period of 6.7 years orbiting the system V729 Cyg from long-term VLA observations. Kennedy et al. (2010) estimated the mass function related to the third body as $3.2 M_{\odot}$. By using this mass function value and the physical parameters given in Table 4 the mass of the third body for $i_3=90^{\circ}$, 70° , 50° , 30° is obtained respectively as $24 M_{\odot}$, $26 M_{\odot}$, $35 M_{\odot}$, $68 M_{\odot}$. We would like to emphasize that the uncertainty in these mass values is high because of the uncertainty in the mass function.

Single massive stars above an initial mass of $8M_{\odot}$ are known to evolve towards an explosive supernova explosion (Smartt et al. 2009). Leaving a neutron star or black hole remnant. However if a massive stars is a member of binary like V729 Cyg its evolutionary path towards the final supernovae will become significantly different. The nature of the final stellar remnant may also be altered so that while a neutron star might be expected mass transfer may lead to black hole formation. Observations of systems such as V729 Cyg will allow us to refined out binary evolutionary models to increase our understanding of the possible variety of stellar lifecycles (see Eggleton 2010, Eldridge & Stanway 2009, Yakut & Eggleton 2005, Pols et al. 1995)

Acknowledgments

The authors thank Peter Eggleton, Chris Tout and Belinda Kalomeni for their valuable comments and suggestions to improve the quality of the paper. We are grateful to an anonymous referee for comments and suggestions which

helped us to improve the paper. This study was supported by the Turkish Scientific and Research Council (TÜBİTAK 111T270 and 113F097) and the TÜBİTAK National Observatory (T60-Pr68). KY thanks the Institute of Astronomy, University of Cambridge for its support during his visit to IoA. The current study is a part of PhD thesis of B. Yaşarsoy.

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Table 1: UBVRI measurements of V729 Cyg (Fig. 1). The phases were calculated using Eq. (1). 1, 2, 3, 4, and 5 denote U, B, V, R, and I filters (F), respectively. All data is published in its entirety at The Strasbourg astronomical Data Center (CDS). A part of table is shown here for guidance regarding its form and content.

HJD	Phase	Δm	F
24 00000+		mag	
53301.3054	0.5115	1.2930	1
53301.3067	0.5151	1.2840	1
53301.3080	0.5187	1.2610	1
53301.3093	0.5224	1.2500	1
53301.3106	0.5260	1.2300	1
53301.3119	0.5296	1.2050	1
53301.3133	0.5333	1.1840	1
53301.3146	0.5369	1.1690	1
53301.3159	0.5405	1.1560	1

Table 2: Times of minimum light for V729 Cyg.

HJD Min	Ref	HJD Min	Ref
14228.269	1	37563.530	4
15257.350	1	37583.369	3
28749.154	1	37959.387	3
29553.985	1	38256.520	3
32747.167	2	38289.327	3
34218.463	2	38322.265	3
34264.849	1	40413.796	2
37253.276	3	48301.616	5
37464.480	4	48555.665	5
37497.520	4	53985.493	6
37550.460	4	56100.454(4)	7
		56103.562(3)	7

References for Table 2. 1- Sazonov (1961) 2- Hall (1974) 3- Haeussler (1964) 4- Romano (1969) 5- ESA, Hipparcos 6- Heubscher & Walter (2007) 7- present study.

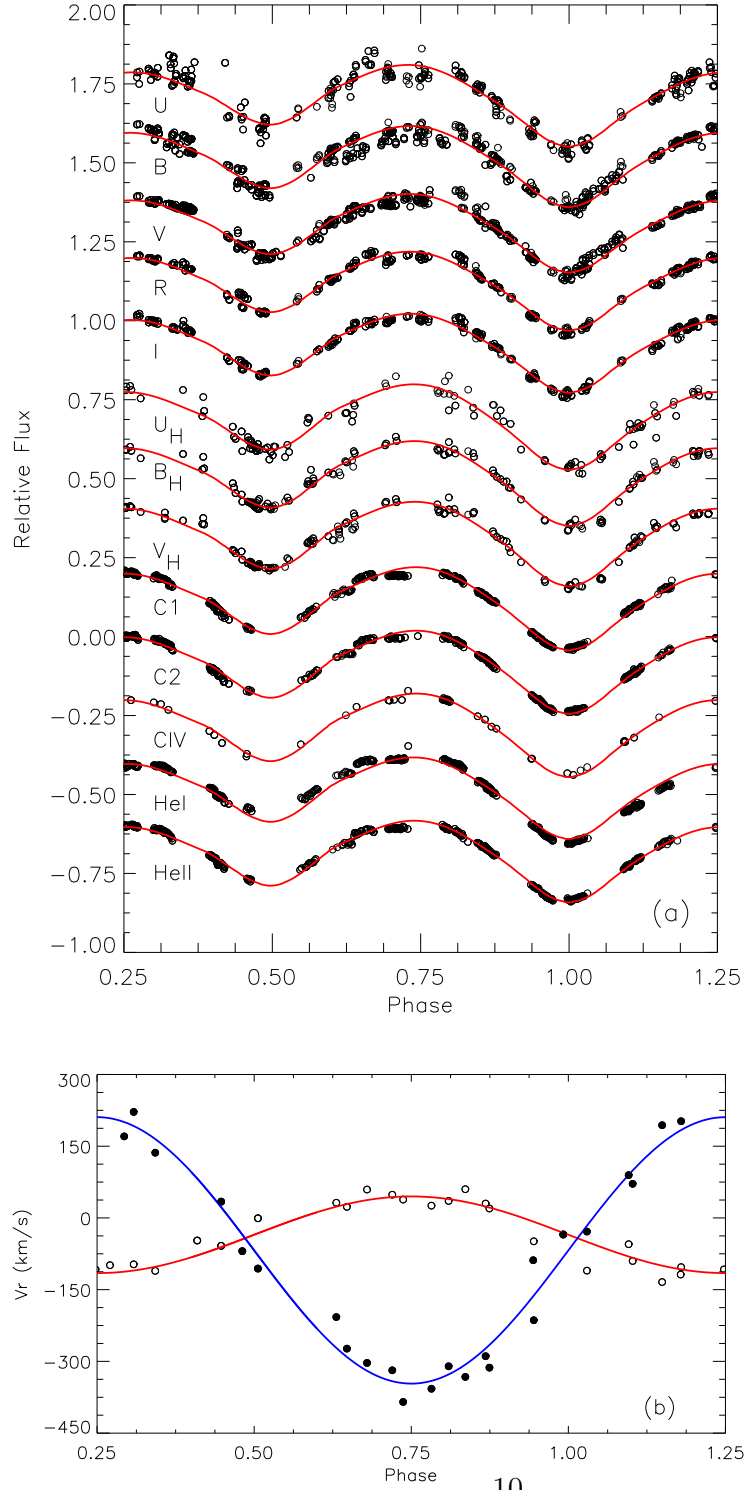


Figure 1: (a) Observational (open circles) and computed (solid line) all available light (a) and radial velocity (b) curves of V729 Cyg.

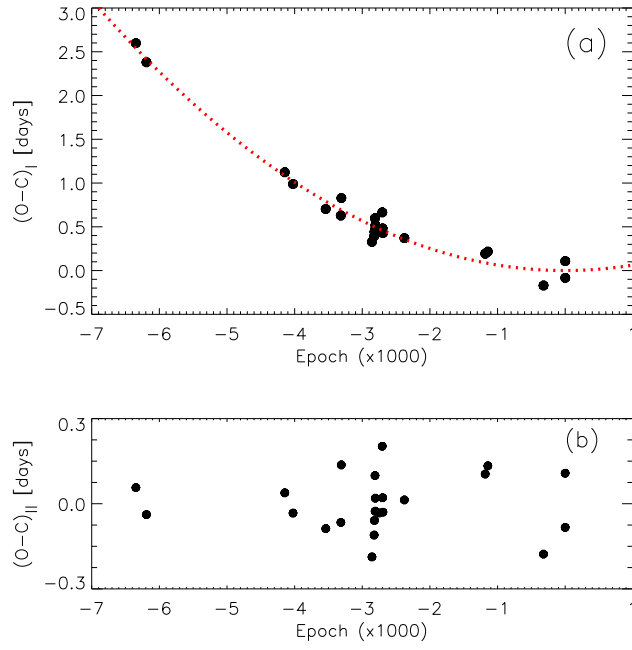


Figure 2: (a) The times of minimum light of V729 Cyg. The dotted line is the best-fit parabola. The total time interval is ~ 115 yr. (b) The difference between the observations and the quadratic ephemeris.

Table 3: The photometric and spectroscopic elements of V729 Cyg with their formal 1σ errors. See text for details.

Parameter	$T_1 = 28000$ K	$T_1 = 32000$ K	$T_1 = 36000$ K
T_o	24 40413.799(5)	24 40413.798(5)	24 40413.799(5)
P (day)	6.597983(3)	6.597982(2)	6.597982(2)
Spectroscopic parameters:			
K_1	82.0(2.3)	79.9(2.2)	88.0(2.3)
$V_{\gamma 1}$	-33.3(3.3)	-33.3(3.3)	-35.10(3.3)
K_2	282.9(8.3)	285.2(8.6)	285.7(8.6)
$V_{\gamma 2}$	-68.0(6.7)	-68.0(6.7)	-67.8(6.7)
Geometric parameters:			
i ($^\circ$)	63.8(1)	63.9(1)	64.1(1)
a	53(2)	53(2)	53(2)
q	0.290(12)	0.290(12)	
$\Omega_{1,2}$	2.406(4)	2.408(5)	2.414(7)
Filling factor (%)	21(2)	20(2)	17(3)
Fractional radii of the primary component			
r_1 pole	0.4665	0.4661	0.4647
r_1 side	0.5042	0.5036	0.5017
r_1 back	0.5318	0.5311	0.5286
\bar{r}_1 (volume radius)	0.5001(4)	0.4996(5)	0.4977(6)
Fractional radii of the secondary component			
r_2 pole	0.2672	0.2668	0.2653
r_2 side	0.2794	0.2789	0.2771
r_2 back	0.3193	0.3184	0.3151
\bar{r}_2	0.2878(4)	0.2872(6)	0.2851(6)
Radiative parameters:			
T_2 (K)	21540(375)	24085(420)	26620(480)
Albedo* ($A_1 = A_2$)	1.0	1.0	1.0
Gravity brightening* ($g_1 = g_2$)	1.0	1.0	1.0

* Fixed

Table 4: Absolute parameters of V729 Cyg. The standard 1σ errors in the last digit are given in parentheses.

Parameter	Unit	Pri. (OIa)	Sec. (O/WN9)
Mass (M)	M_{\odot}	31.6(2.9)	8.8(3)
Radius (R)	R_{\odot}	25.6(1.1)	14.5(1.0)
Temperature (T_{eff})	K	28000	21263(370)
Luminosity ($\log L$)	L_{\odot}	5.558(65)	4.587(96)
Surface gravity ($\log g$)	CGS	3.12(2)	3.06(2)
Absolute bol. magnitude (M_b)	mag	-9.16	-6.74
Absolute vis. magnitude (M_V)	mag	-6.50	-4.89
Separation between stars (a)	R_{\odot}	50.8(1.8)	
Distance (d)	pc	932(20)	